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An Empirical Study Investigating the Impact of Micro-algal Technologies and their Application within Intelligent Building Fabrics

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Abstract

The potential for algal technologies to lead innovation in bio-mimetic design requires much further analysis. This paper investigates the potential of the use of algal technologies in the building sector as part of an on-going research study. This investigation restricted itself to the application of algal technologies as catalysts for architectural creativity in the design of intelligent building fabrics and the resulting influence on internal luminance. In its attempt, the research study integrated both quantitative and qualitative approaches and was thus based upon a mixed method research. The paper outlines the initial empirical study, the primary purpose of such being the investigation of algal growth mechanisms and the examination of any interdependence that exists between culture density and internal luminance. Through the construction of a highly controlled experimental chamber, the authors were able to successfully examine this relationship and thus develop a visual design tool that informs what action should be taken or strategy employed based on the clients shading requirements and specific technological framework. It was established that from such work that as culture density increased, the technological strategies light transmittance decreased proportionally.

Peer-review under responsibility of IEREK, International experts for Research Enrichment and Knowledge Exchange.

Keywords: *Micro-algal Technologies; Intelligent facades; Empirical Study; Building Monitoring; Innovative design*

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1. Introduction

Although major studies on the various applications of algae began as long ago as the early 1970's following the 1973 oil crisis, (Nagle and Lemke, 1990: 355) extensive scrutiny into its use remains on the cutting edge of technical research with the prospect of attaining a commercially viable approach to carbon neutral energy generation remaining uncertain. (Lee, 2012)

Human induced climate change is now far more evident with analysis presenting the effects of global warming arising faster than expected (Pittock, 2009) as the earth's system is "forced across thresholds" (Becken and Hay, 2007: 19) it can not withstand. Societies greatest challenge shall be how effectively and swiftly it can significantly reduce its Carbon Footprint through enhanced architectural design. The importance of opening channels of discourse on the subject of human-induced climate change is pivotal to the success of these efforts.

Although the empirical study presented within this paper represents 10 weeks of investigation, the data presented was collected during a single preliminary experimental week as presented in Section 4.3. For the purpose of clarity, external luminance is defined as the luminance recorded on a horizontal plane from an unobstructed sky, glazed luminance is defined as the luminance recorded on a horizontal plane at the base of the glazed aperture whilst internal luminance is defined as the luminance recorded at the rear of the experimental chamber.

It should be noted however, that other fields of study supported this preliminary experimental work. In this respect, extensive time was dedicated also to the conduction of several antecedent studies on algal growth, shading pragmatism and experimental chamber construction, these studies being essential to the success of the central empirical study.

Data supports the application of algal technologies as daylight regulators within architectural frameworks and presents a cross-culture density average daylight factor of 17%. Average daylight factors of 19.3%, 21.2%, 12.3%, 18.6% and 15.4% were monitored and established for culture densities 5 grams, 10 grams, 15 grams, 20 grams and 25 grams respectively.

Through the employment of Pearson's Correlation Co-efficient, a moderate to strong negative correlation of magnitude -0.6 is the results was distinguished between increasing algal density and internal luminance. However, only a very weak relationship was established between algal density and the influence this has on reducing the non-application event daylight factor. The non-application event daylight factor defined here as: the daylight factor calculated for each individual empirical experiment without the applied algal technology. For the purpose of clarity, a technologies ability to reduce the non-application event daylight factor shall be noted from this point as the technologies shading efficiency. (Equation. 1) These phenomena as well as other comprehensive relationships are discussed further in Section 5

$$\text{Shading Co-efficient} = \frac{\text{Non Application Event Daylight Factor}}{\text{Application Event Daylight Factor}} \times 100 \qquad (1)$$

Equ. 1 Shading Efficiency Equation

Through the analysis conducted in Section 5, southern facades are presented as those possessing the optimum ability to successfully and appropriately shade. It shall also be presented that those technologies when solar oriented could play host to significantly enhanced culture densities without resulting in excessive reductions to internal luminance.

1.1. Background

The extraction of usable energy generating materials from micro-algae is based on two prevailing schools of thought; open ponds as seen in Fig. 1. (a) and closed loop photo-bioreactors seen in Fig. 1. (b) (Ginley and Cahen, 2011: 321) Both are based upon the extent to which algae's growth is controlled, although in practice many systems fall somewhere in between these two polar philosophies. Raceway pond applications are most commonly used

(Singh, 2013: 90) due to their flexibility, are relatively simple to construct and are traditionally composed of a shallow trough in the shape of an elongated race track.

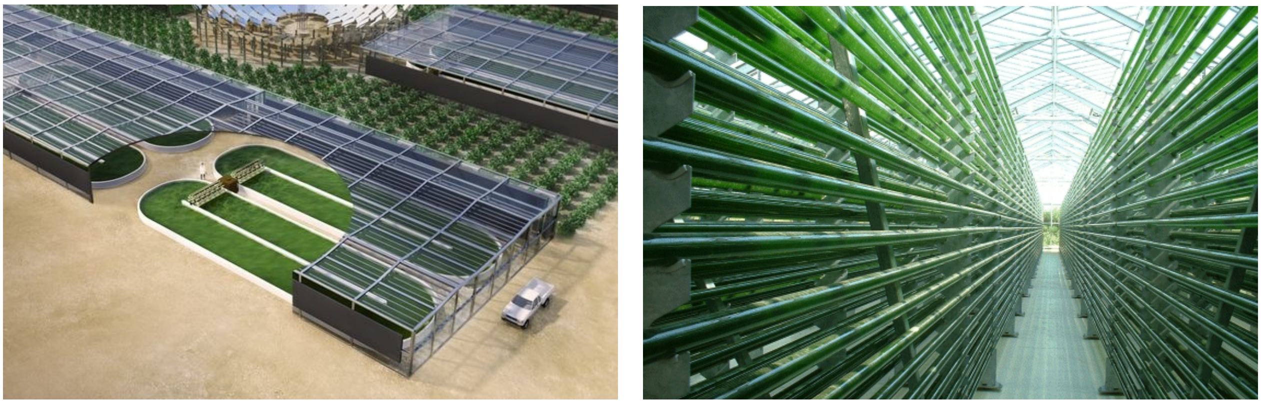


Fig. 1. (a) Industrial Algal Biofuel Generation, Raceway Pond (Common Territories, 2011); (b) Industrial Algal Biofuel Generation, Photo-bioreactor (Kay, 2012)

The use of low voltage spinning wheels maintains culture agitation to reduce stagnation and ensure exposure to daylight. (Demirbas and Demirbas, 2010: 84-86) The complexity of both CO2 and heating delivery can be varied whilst daylight may be subsidised or replaced with artificial sources. The majority of proposals however forgo such sophistications and so have inherently lower costs. Cost of construction, approximately $100,000 per hectare for raceway pond applications compared to $1 to $1.5 million per hectare for photo-bioreactor applications, (Aresta et al, 2012: 84) remains the primary strength of this approach.

Raceway pond strategies do, however, possess weaknesses that significantly diminish their application. These are intrinsically connected to the level of control employed and are alleviated only through the escalation of controlling a measures, energy requirements and thus construction costs. Growth rates of 30 grams per square meter per day (Kyndt and D'Silva, 2013) remain the primary weakness of raceway pond applications. This is compounded by culture fragility (Wang and Ma, 2011: 133) with the ever-present likelihood of culture crash leading to increased inefficiencies. (Gordon and Seckbach, 2012: 185)

An innovative approach has emerged that aims to provide greater control over the scale and rate of algal growth with little or no increase in relation to economic or energy costs. It is proposed that industrial scale raceway pond applications may prosper from close geographical proximity to modern power stations. (Rackley, 2009, 320-325) This theory presents that algal technologies will benefit greatly from the concentrated source of CO2 (Johansson et al, 2012: 1772) as well as the potential use of heat extracted from industrial processes for the purpose of temperature control and dry weight biomass manufacture, (Posten and Walter, 2012: 75-77) all the while providing an opportunity for what are traditionally harmful emissions to provide a redeeming function. (Solomon, 2011: 114)

Although similar in theory, there are distinctions that make photo-bioreactor applications far more complex to construct and they therefore possess elevated energy requirements (Zah, 2010: 109) and significantly higher operational costs. (Kole et al, 2012: 662) These strategies do, however, possess much noteworthy strength that supports the papers dedication to scrutinise their application. Photo-bioreactor applications possess considerably higher volumes of per square meter algal growth of 50 grams per day. (Pandey et al, 2013) Approximately 40-50% higher than growth rates expected within raceway pond applications (Kyndt and D'Silva, 2013) and driven in part by the highly controlled environment where everything from heat and algal agitation to levels of carbon dioxide and fertiliser are governed electronically, photo-bioreactor applications allow a greater diversity of algal strains to be cultivated throughout many contrasting climates, (Gordon and Seckbach, 2012: 185) many of whom are unsuitable for the application of raceway pond systems.

2. Algal Technologies and Bio-Mimetic Design

The potential for algal technologies to lead innovation in bio-mimetic design and drive a revolution in kinetic architecture requires extensive scrutiny. The subject of algae remains on the cutting edge of large-scale energy generation, let alone its application within the context of the built environment. Concomitantly, there inevitably exists a significant gap in knowledge. It is apparent that the research gap lies not in the credibility of algal biofuel systems on a biological platform but in how algae can be used not only as a source of fuel but also as a catalyst for architectural creativity in the design of intelligent building fabrics. The architectural professions now faces a context in which building schemes are emerging that embrace algae as both an energy generator and as part of the building aesthetic, with very little research underpinning these efforts.

3. Empirical Study

Literature analysis presents a modular algae configuration depicted in Fig. 2. as that most suited to further analysis, nominated for its enhanced suitability for external cultivation, greater mass transfer and reduced energy needs due to its increased luminance surface area and airlift carbon dioxide administration. (Lee, 2012: 711. Pandey et al, 2013)

As a bio-synthetic organism, algae thrives on elevated light intensity and it is important therefore to distinguish and validate the narrow technical and environmental ranges in which the empirical study shall be conducted. Eastern, western and southern facades experience greater magnitudes of solar radiation (Kock-Nielsen, 2013: 45. Sayigh, 2013: 440. Kalogirou, 2013: 359) and were therefore prioritised for investigation.

Fig. 2. Modular Algae a Synthesis between Biology, Architecture and Engineering

The primary objective of the research is to demonstrate the relationship between algal density within solar responsive fabrics and its effects on internal luminance and from these efforts attempt to establish a reliable framework from which the predictable use of algal technologies can be forecasted. The research shall also attempt to establish the relationship between culture density and light quality. The authors were able to fully examine these relationships through sound experimental data. It was expected that there would exist strong negative correlation between culture density and the magnitude of light experienced within the chamber. This was later proved as shall be outlined in Section 5 of this paper.

4. An Empirical Study within a Highly Controlled Experimental Chamber

The experimental procedure was conducted in the city of Lincoln, the administrative centre of the county of Lincolnshire. As is the case in any empirical study conducted within the external environment, it was the construction of an experimental chamber that maintained a level of internal control over a five-week experimental phase that posed the most formidable challenge. Preliminary testing was necessary therefore to distinguish the most effective strategy for the construction of a resilient experimental chamber. The rig designed and constructed constituted a rigid rectangular chamber of internal dimension 1200mm x 1200mm x 2400mm. The chamber was constructed of six prefabricated panels painted white, each panel connected using a simple screwed butt joint as depicted in Fig. 3., this nominated for its simplicity (Chan, 2002: 43. Churchill, 2003: 90). These measures were taken to ensure a uniform environment in which to test.

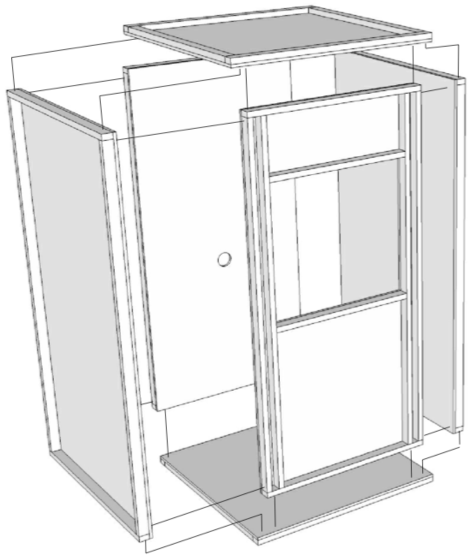


Fig. 3. Design and Construction, An Axonometric Representation

The chambers anterior panel possessed a single glazed aperture of dimension 928mm (W) x 880mm (H), situated 1098mm from the ground and equidistant from each wing. Designed thusly to constitute approximately 28% of the internal wall area, close to the optimum ratio for reduced energy requirements through daylighting, (Ghisi and Tinker, 2001), light entering the chamber was recorded through an 80mm circular void in the chambers posterior panel, this void positioned 800mm from the ground, a suitable height at which to conduct daylighting. (Ibarra and Reinhart, 2009, 198)

4.1. Nannochloropsis Occulata Cultivation and the Efficiency of Small Scale Photo-bioreactors

Although a multitude of algal specimens are attainable, quality control rendered a great deal of these redundant. When naturally sourced, algae hosts a multitude of unwanted coliform bacteria (Boyd, 1998: 482) that influence greatly the cultures uniform transmittance and would so invalidate much of the experimental data. To eradicate these concerns, six weeks were dedicated to the cultivation of a highly controlled sample through a study of great value, significance and detail.

First described by Hibbered in 1981 (Wehr, 2002: 427) as a specimen with elevated potential for renewable oil generation, (Chen and Sun, 2013: 44) Nannochloropsis Oculata was nominated primarily due to its shorter growth cycle, (Singh, 2013: 76) higher lipid content (Cohen, 1999: 47) and relative robustness (Borowitzka and Moheimani, 2012: 81) that facilitate its growth within varying climatic conditions. (Burnell and Allan, 2009)

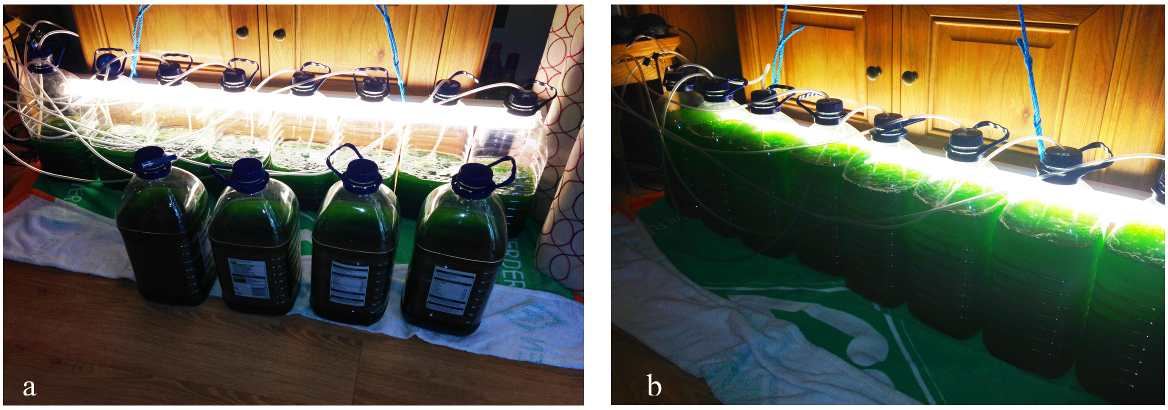


Fig. 4. (a) Experimental Rig Design for Algae Growth; (b) A Representation of Culture Expansion

Commencing as three separate 500ml cultures, (Mak, 2014) each was maintained and advanced within highly controlled conditions possessing environmental parameters within very narrow ranges. Maintained at temperatures between 19º and 21º, carbon fixation was driven primarily by engineered algal fertilisers and continuous aeration, carbon sequestration aided here by the use of a small air rock in each bioreactor. (ZM Systems, 2013) Daylight was also unconditionally restricted, artificial light supplied through a mechanical phased system using a 36W fluorescent light. (Fig. 4. (a))

Nannochloropsis Oculata possesses a critical density growth cycle of 5 to 7 days. (Snell, 2004) On completion of each 7-day incremental growth phase, each culture was doubled in volume and supplied with engineered fertiliser. This cyclical process presented in Fig. 4. (b) was maintained until the critical volume of 30 litres was achieved. The critical volume was distinguished thusly to ensure a 10 litre specimen could be extracted for use within the primary empirical study without compromising the central cultures ability to advance again to the critical volume over the following growth phase.

4.2. Preliminary Testing for Shading Pragmatism

It is worth noting at this point that an obvious lack in knowledge of how culture density may influence the efficiency of solar responsive building fabrics made defining the boundaries and limits of certain experimental variables impossible. Conducting antecedent tests was integral therefore to gain an understanding of the suitable experimental parameters.

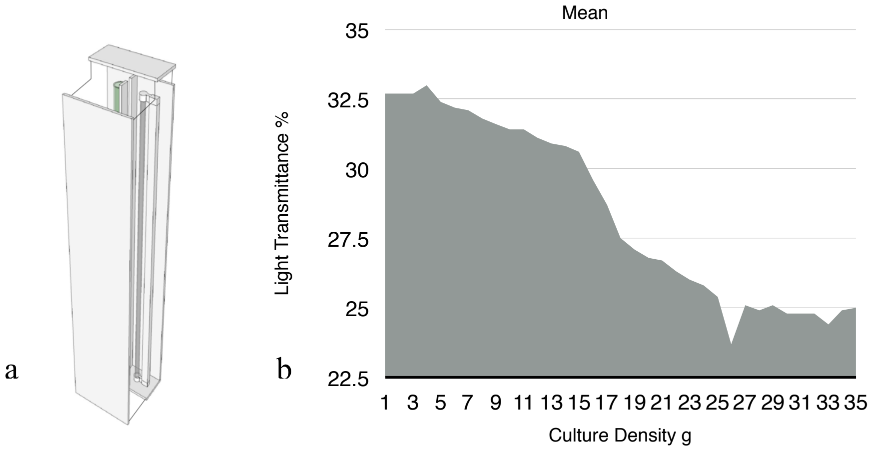


Fig. 5. (a) Antecedent Chamber - An Axonometric Representation; (b) Comparative Analysis between Light Transmittance and Culture Density

To be conducive to the experimental methodology, this work was based upon an empirical study. Two separate chambers were constructed. The posterior chamber played host to a 36W fluorescent light and was entirely enclosed whilst the anterior chamber played host to a single acrylic tube that accommodated varying algal culture seen in Fig.5. (a).

Fifteen individual studies were conducted on algal densities, difference of 1 gram per metric litre to 35 grams per metric litre were tested to establish the isolated light transmittance of each culture density. A strong linear relationship was found between increasing culture density and reducing light transmittance between culture densities of 5g/l and 27 g/l, with particular velocity experienced between 13g/l and 20g/l. It was also confirmed that the effect of varying culture density above and below the boundaries 5g/l and 27g/l is minimal as depicted in Fig. 5. (b).

With a cross population standard deviation of 0.22%, instance population derived standard deviations varying from 0.07% to 0.72%, and a cross population range value of 0.83%, again instance population derived range values varying from 0.17% to 3.02%, it can be successfully argued that the antecedent study was intelligently designed and successfully conducted with all data collected within this study retaining a great deal of validity, reliability and statistical probability. Following the collection of such reliable data, the final experimental parameters were established as 5g/l and 25g/l with four equal intervals between these.

4.3. Experimental Process

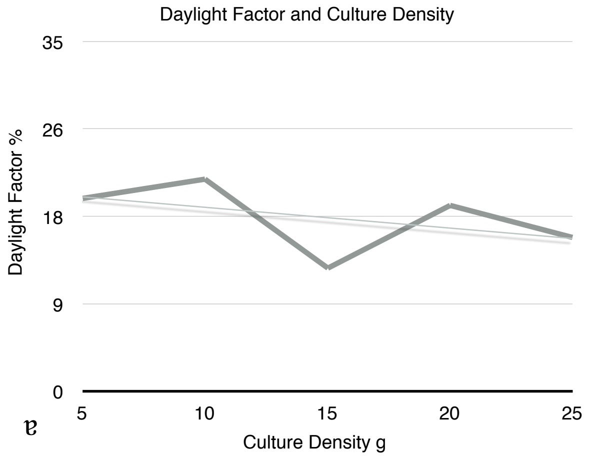
The empirical study was conducted within a homogeneous and highly controlled experimental chamber to ensure scientific credibility. Positioned in a secure environment and connected to the southern facade of the Lincoln School of Engineering at the University of Lincoln so as to avoid the likelihood of passive shading, (Fig. 6.) the experimental chamber ensured that all potential experimental defects that could themselves yield a multitude of undesirable variables were avoided. The central empirical study was conducted for a duration of five weeks, each week playing host to cultures possessing one of five densities. Data was collected each day within this time. Although recorded in the same manner, the experimental data presented throughout this paper was collected within a single preliminary experimental week with each individual weekday-playing host to one of five culture densities. Data on external luminance, glazed luminance and internal luminance was recorded every hour between 10:00am and 17:00pm from 26th to the 30th May 2015. The data was collected using a Precision Gold light meter, the data logger possessing an accuracy of between ±5% to ±10%.

It was in this data's analysis in which the principles of parsimony (Aarts, 2007) were sought most readily to enable the postulation of analyses that were remarkably simple yet effective. Difficulties arose due to the variability of weather patterns where cloud conditions, the presence of water vapour and even pollutants can influence the intensity of solar radiation. (Tregenza and Loe, 2013: 31) It was essential therefore to construct an initial relationship between internal and external luminance before any credible relationship could be established between culture density and daylight. Daylight factor and Pearson's Correlation Co-efficient analysis was employed therefore to effectively distinguish a comprehensive scientific relationship between the phenomena under consideration.

Fig. 6. The Experimental Chamber in-situ within the University of Lincoln Campus

5. Algal Density and its Influence on Internal Luminance

Average daylight factors of 19.3%, 21.2%, 12.3%, 18.6% and 15.4% were recorded for culture densities of 5 grams, 10 grams, 15 grams, 20 grams and 25 grams respectively. {Fig. 7. (a)} Through the employment of Person's Correlation Co-efficient analysis, a moderate to strong negative correlation of magnitude -0.6 was established between daylight factor and culture density. In slight contradiction to this however is the very weak relationship, of co-efficient -0.3, established between algal density and shading efficiency. In fact, with an average shading efficiency of 44%, this representing an average shading co-efficient of 56%, a culture density of 15 grams was established as that most equipped to shade. {Fig. 7. (b)}



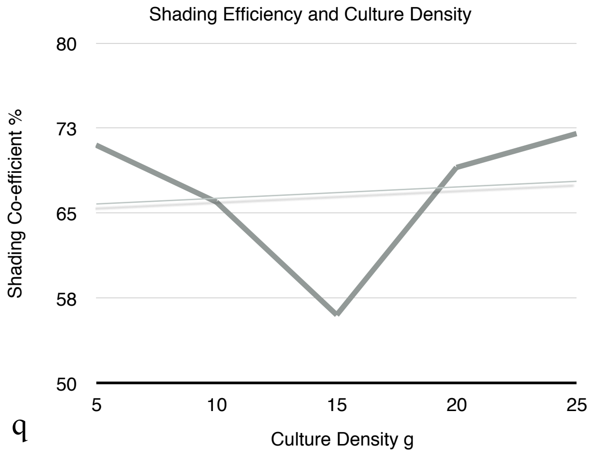


Fig. 7. (a) A Cross Comparative Analysis between Daylight Factor and Culture Density; (b) A Cross Comparative Analysis between Shading Efficiency and Culture Density

This suggests the need for further testing to establish a better understanding of the linearity of the daylight analysis. In support of this requirement is an analysis of internal luminance. As a matter of logic, it should be expected that as culture density increases, internal luminance, as expressed here in lux, shall decrease proportionally. This is however not the case. There is in fact weak positive correlation of co-efficient magnitude 0.3 between culture density and internal luminance. {Fig. 8. (a)} This data should be treated as flawed and supports the authors' dedication to conduct further investigation. This will give the data greater depth and shall enable the alleviation of issues faced through momentary extremes in environmental conditions.

This concise analysis supports the postulation of a methodology that is routed in cyclical analyses that are founded upon normalised data outputs, the normalised output in this case being daylight factor. Whilst there exists not relationship between culture density and internal luminance, there does exists a relationship in some manner between culture density and daylight factor.

Cross density average application event light transmittance, in this case defined as the difference between glazed luminance and internal luminance, as defined in Section 1, was established as 25%. {Fig. 8. (b)} This contrasts with the cross density average non-application event light transmittance of 37%. Strong negative correlation of co-efficient magnitude -0.8 was established that supports the notion that as culture density increases, light transmittance decreases proportionally.

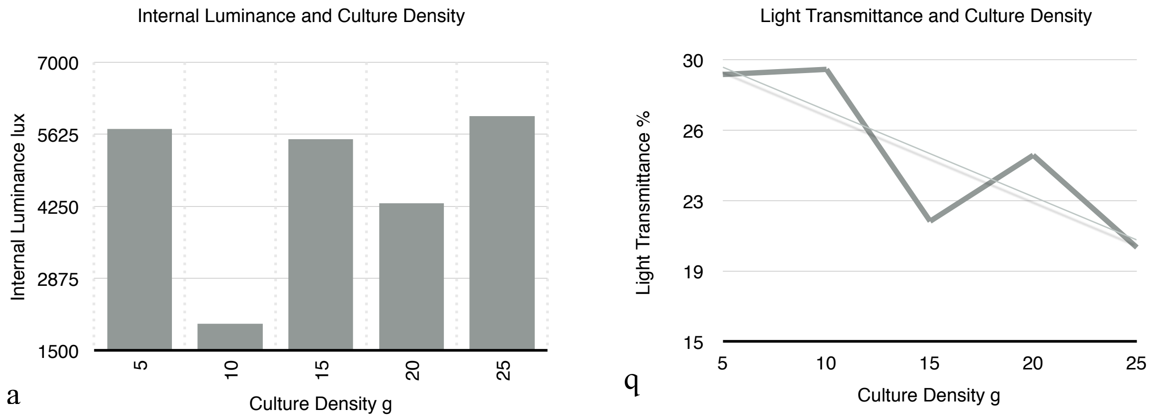


Fig. 8 (a) A Cross Comparative Analysis between Internal Luminance and Culture Density; (b) A Cross Comparative Analysis between Light Transmittance and Culture Density

5.1. Algal Density and Temperature

Although it was not stipulated as a central objective within the empirical methodology, it became apparent through analysis that there existed a relationship between temperature and daylight regulation

There exists moderate negative correlation of co-efficient magnitude -0.5 between temperature and daylight factor depicted in Fig. 9. (a). This is supported by moderate positive correlation of co-efficient magnitude of 0.55 between temperature and shading efficiency, this representing moderate negative correlation of identical magnitude between culture density and shading co-efficient depicted in Fig. 9. (b). This supports the notion that as atmospheric temperature increases, so does the shading efficiency of each technological strategy.

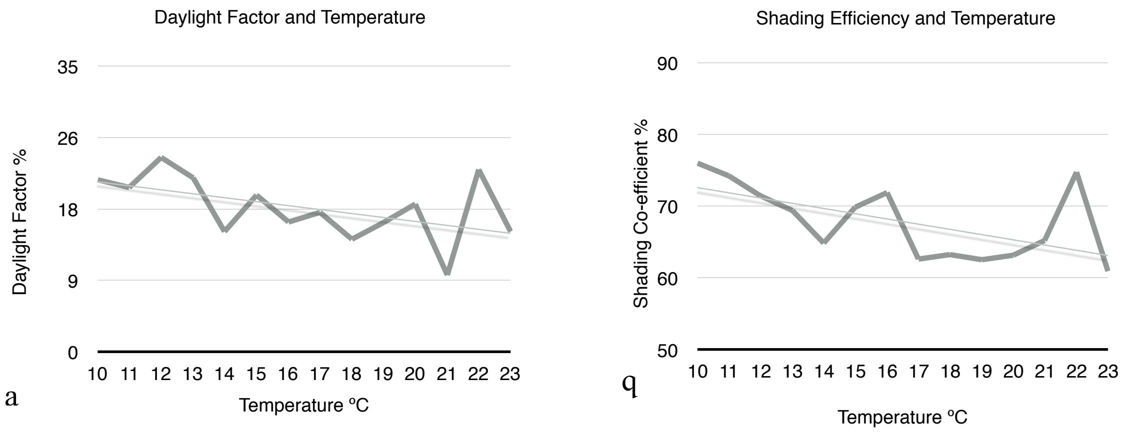
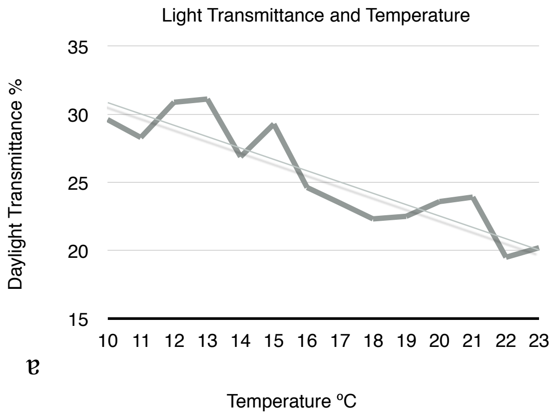


Fig. 9 (a) A Cross Comparative Analysis between Daylight Factor and Temperature; (b) A Cross Comparative Analysis between Shading Co-efficient and Temperature

This proposition is further supported by extremely strong negative correlation of co-efficient magnitude -0.9 between temperature and light transmittance seen in Fig. 10 (a). Although the authors in no way propose this data as a comprehensive conclusion, it is apparent that temperature is an experimental variable that requires further empirical analysis not only as part of this research programmes continued work but within an independent research project.



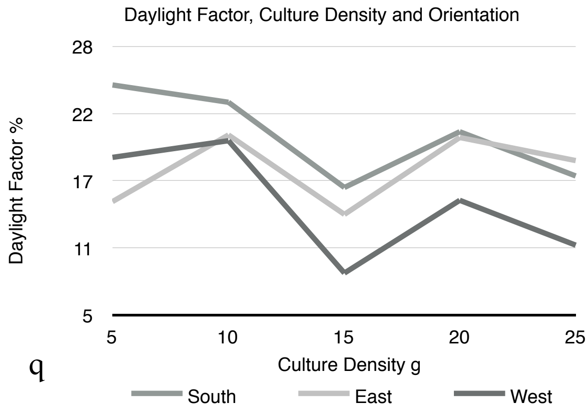


Fig. 10. (a) A Cross Comparative Analysis between Light Transmittance and Temperature; (b) A Cross Comparative Analysis between Daylight Factor, Culture Density and Solar Orientation

5.2. Algal Density and Shading Efficiency

In order to fully understand the interdependent relationship that exists between culture density and daylight, it was critical to conduct a more thorough analysis of shading efficiency. Although it has been initially established that there exists no discernible relationship between culture density and shading efficiency, there was established a cross density average shading co-efficient of 67%. There was established also a cross density average internal luminance of 4707 lux and a cross density average daylight factor of 17%.

If we are to consider that the average required daylight factor and internal luminance of an office space are approximately 6-10% and 300-500 lux respectively (Thomas, 2006: 97. Joshi, 2008: 465. Jain, 1993: 43), it can be argued quite successfully that algal technologies are not only capable of being employed within an architectural framework as a shading mechanism but that these technological strategies could play host to significantly elevated culture densities.

5.3. Culture Density and Orientation Parameters.

Although it has been established that there exists a moderate to strong relationship between culture density and daylight factor, it is the authors' opinion that this relationship is in no way strong enough to retain scientific credibility. The gaining of a more comprehensive understanding of the phenomena under consideration and thus the presentation of a more credible relationship was established through a wider analysis of orientation parameters.

Although there exists a relationship of greater strength between culture density and daylight factor when considered inclusively of orientation parameters, there too exists a distinction between the technical performance of algal technologies when applied within varying orientations. It has been established across all but one culture density, that higher daylight factors should be expected when the prescribed technical solution was applied on a southern orientation. {Fig. 10 (b)} It was found also that those technical solution applied on southern orientations possessed an enhanced shading efficiency. Shading co-efficients of 62.9%, 71.2% and 70.62 were established southern, eastern and western orientations respectively. This analysis supports the notion that algal technologies are most effectively employed when oriented south and would possess an enhanced ability to shade appropriately.

5.4. Culture Density and Solar Orientation

For the purpose of clarity, solar orientation shall be defined from this point as the orientation of the experimental chamber towards the sun. In this capacity, there is evidently a relationship between daylight factor and regulation and solar orientation. Inclusive of all culture density parameters, it was found that solar oriented spaces possessed an average daylight factor of 21.1%, much greater than for spaces shaded, these areas possessing an average daylight factor of 13.7%. Similar finding were established for each individual culture density depicted in Fig. 11. (a). Hence, shading efficiency analysis supports this proposition. Solar oriented spaces possessed a diminished ability to shade. Whilst solar oriented spaces possessed an average shading co-efficient of 69.9%, shaded spaces possessed an average shading co-efficient of 64%. Again these findings are echoed across each individual culture density seen in Fig. 11 (b). This analysis supports the notion that algal technologies possess a diminished potential to shade solar oriented spaces, this itself validating the proposition of employing elevated culture densities within certain technical applications.

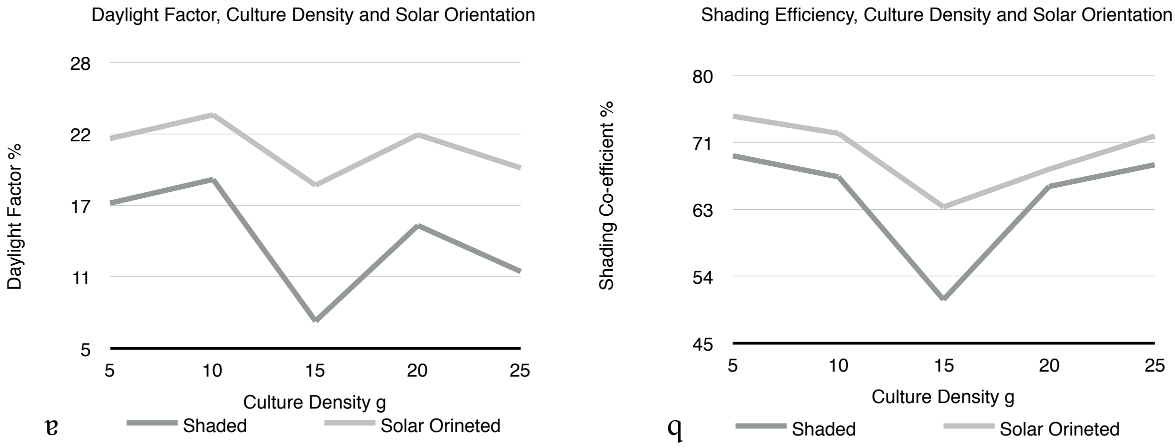


Fig. 11. (a) A Cross Comparative Analysis between Daylight Factor, Culture Density and Solar Orientation; (b) A Cross Comparative Analysis between Shading Efficiency, Culture Density and Solar Orientation

6. Summary of Conclusions and Further Work

The paper presented distinct conclusions over the potential of the use of algal technologies within intelligent building fabrics. The conclusions presented within this paper will act as the foundation from which further data shall be projected, analysed and discussed in future publications.

Possessing an average shading co-efficient of 67%, it is apparent that algal technologies are endowed with the potential to act as daylight regulators within an architectural framework. It is apparent also that there exists the opportunity to employ greatly elevated culture densities within such applications, dependent primarily upon geographical and solar orientation. It is presented that there exists a moderately strong interdependent relationship between increasing culture density and decreasing daylight factor. This proposition has been weakened somewhat however by the presence of a very weak relationship between increasing culture density and increasing shading efficiency, this equating to a weak relationship between increasing culture density and decreasing shading co-efficient. This therefore supports the notion that increased daylight factor should be expected through the application of decreasing culture densities, although it is not known whether this relationship is defined by phenomena as of yet unspecified. A clear criteria of evaluations is set up and presented in section 4 of this paper.

Higher daylight factors experienced within solar oriented spaces, this combined with a reduction in shading efficiency, supports the proposition that solar oriented technical applications may be capable of hosting greatly elevated culture densities and thus act as more efficient growth modules. Conversely, those technical strategies oriented away from direct sunlight have been shown to possess an enhanced ability to regulate daylight through shading. It is presented therefore that those technical strategies oriented south and away from direct sunlight possess the optimum ability to act as both enhanced growth modules and shading components. This research succinct conclusion has presented the potential application of micro-algae as an integral element of intelligent and solar responsive building fabric. Concomitantly, the investigation presented in this paper implies successful application of algal technologies in architectural façade innovation and facilitates more opportunities of supplementary research to gain a comprehensive understanding of how these technologies can be further employed. Future research must address, as a matter of urgency and through mixed-method channels, what influence if any the application of algal technologies may exert on daylight quality. To achieve such ends would require an enlarged research project possessing a wider scope that would enable the investigation of a multitude of technical compositions and a greater spectrum of algal densities, all of which should be tested within experimental and realistic contexts. Particular attention should also be given to the investigation of economic viability and energy generation. Only when significant time is dedicated to these ends shall an extensive understanding of micro-algae's place within the wider framework of architecture and the built environment be attained.

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